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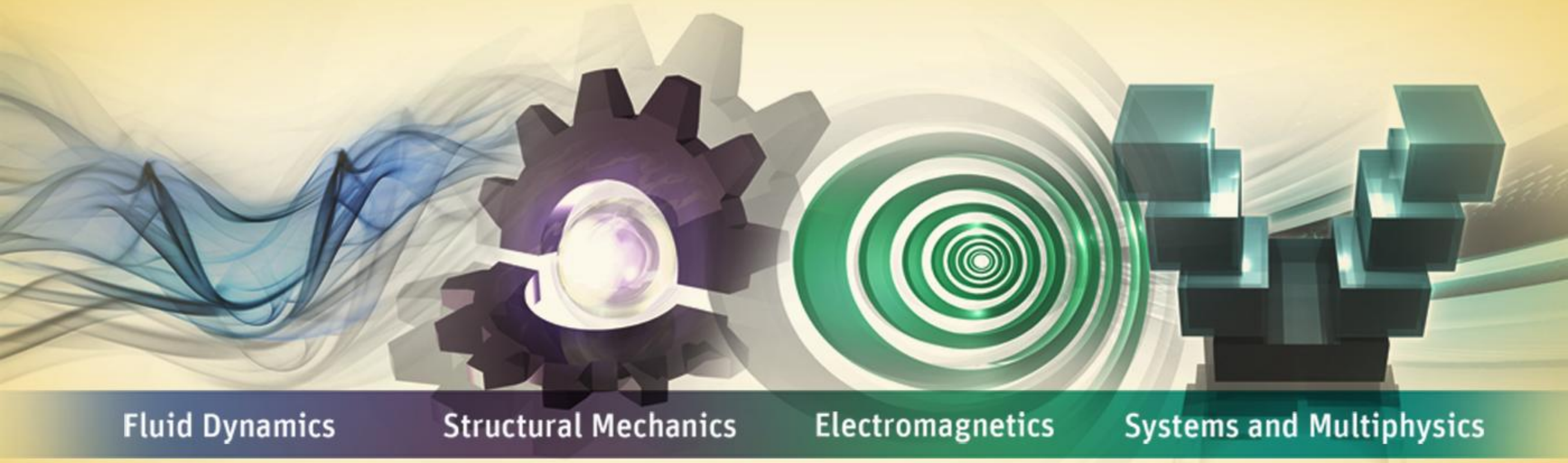
Comparison of Three Numerical Approaches for Modeling Poly-Disperse Dense Particulate Flows



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Overview

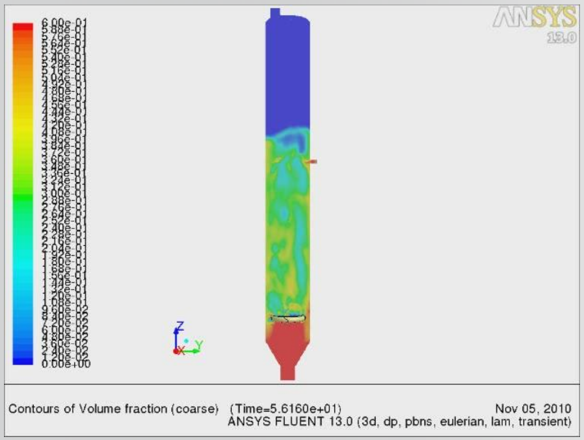
- Introduction and motivation
- Polydisperse particulate flow modeling approaches
- NETL/PSRI Bubbling Fluidized Bed challenge problem
- Results
- Summary

Introduction and motivation

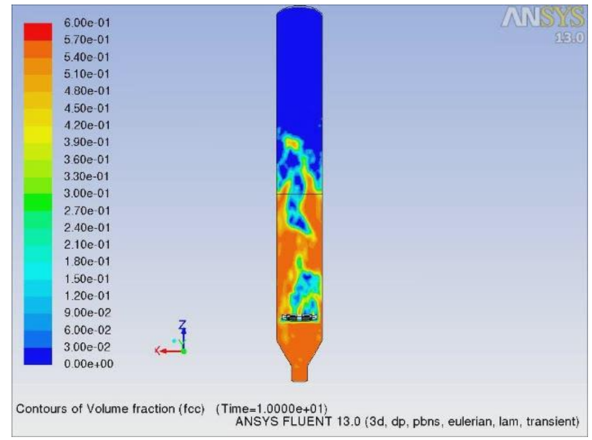
- Widespread occurrence of polydisperse particulate flows
- Modeling platform for polydisperse particulate flows is continuously evolving
- Validation of models for determining
  - range of applicability
  - capability in predicting key flow features under complex conditions and simplifying assumptions
- Ongoing validation efforts
  - Investigation of particle segregation in Circulating Fluidized Bed
  - NETL/PSRI Bubbling Fluidized Bed challenge problem

NETL/PSRI Bubbling Fluidized Bed challenge problem

Euler-Granular with inhomogeneous population balance model

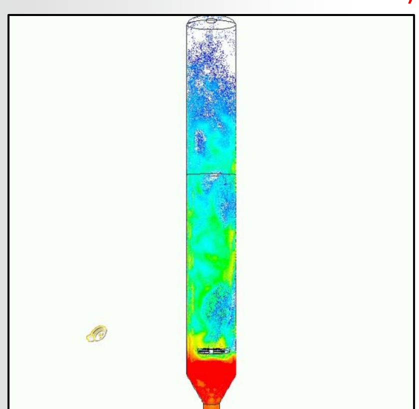


Eulerian-Lagrangian
Dense Discrete Phase Model (DDPM)



Eulerian-Lagrangian
Discrete Element Method (DEM)

(Available in ANSYS Fluent R14.0)



Modeling approaches for dense particulate flows

- **Eulerian-Eulerian**
  - Population balance equations for changes in particle size distribution
  - Aggregation and breakage kernels[1], and particle phase stresses based on kinetic theory of granular flow

- **Solution methods of Population Balance Equations**

  - **Inhomogeneous Discrete (available in ANSYS Fluent 13.0)**

    Extension of standard discrete model to multiple discrete phases

  - **DQMOM (beta feature in 13.0)**

    Transport equations for weights and nodes of quadrature approximation instead of moments of number density function

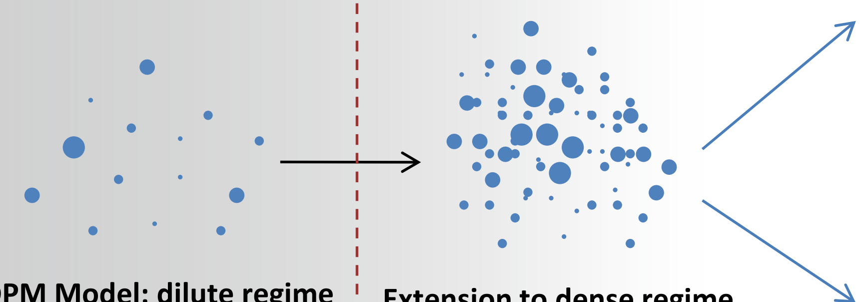
[1] (Fan et. al. 2004)

Modeling approaches for dense particulate flows

- **Eulerian-Lagrangian**
  - **Dense Discrete Phase Modeling (DDPM) framework:**

    Extension of Discrete Phase Model (DPM) to account the effect of disperse phase volume fraction on continuous phase

DDPM framework



DPM Model: dilute regime
Tracking of particles or parcels

Extension to dense regime

Particle-Particle interaction

Solid particles
- Granular kinetic theory based
- Explicit contact (soft sphere model)

  (DEM model in ANSYS Fluent 14.0)

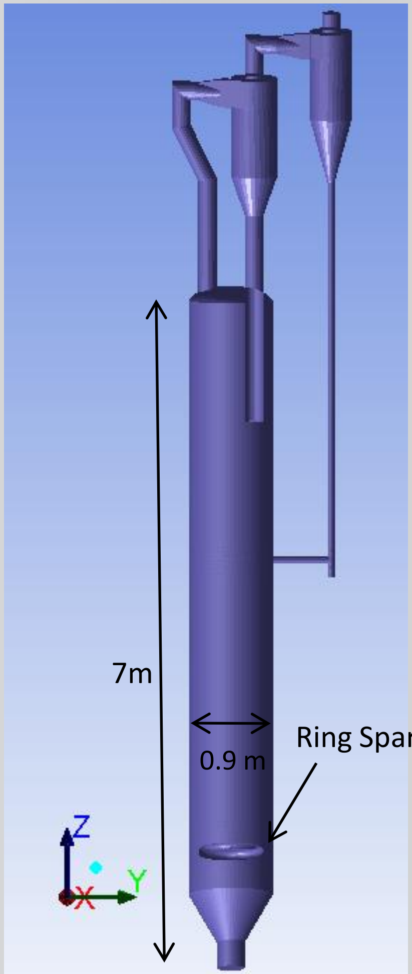
Bubbles or droplets
- Collision/coalescence and break-up models

NETL/PSRI Bubbling Fluidized Bed challenge problem (2010)

- Predicting the differences in fluidization behavior with different bed depths and fines content
  - Bed expansion
  - Gas-streaming
  - Bubbling characteristics

- Challenges
  - Wide particle size distribution
    - 10 micron to 300 micron particles
  - Superficial gas velocity far beyond minimum fluidization velocity
    - 75 to 150 times minimum fluidization velocity
  - Geometry details including air distributor, primary and secondary cyclones

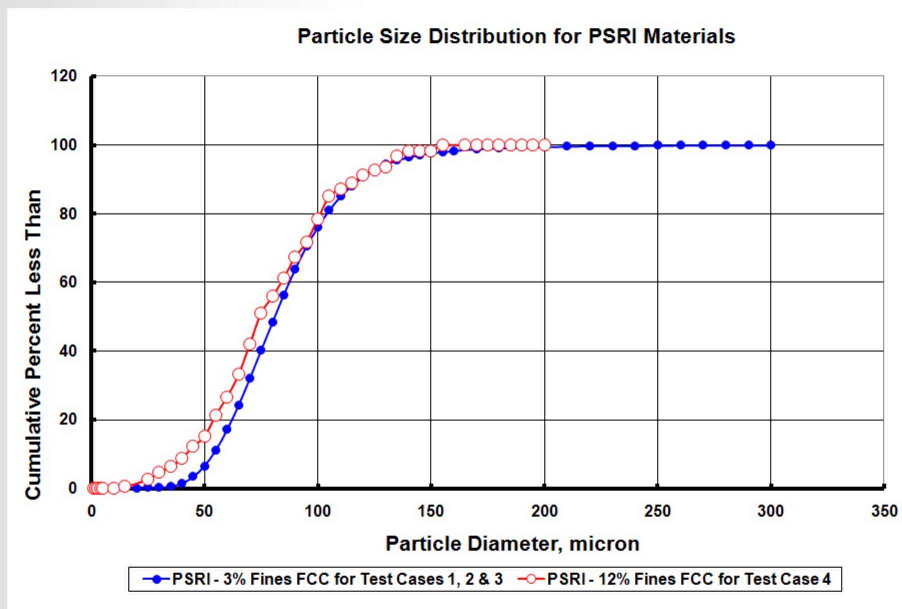
Geometry and test conditions



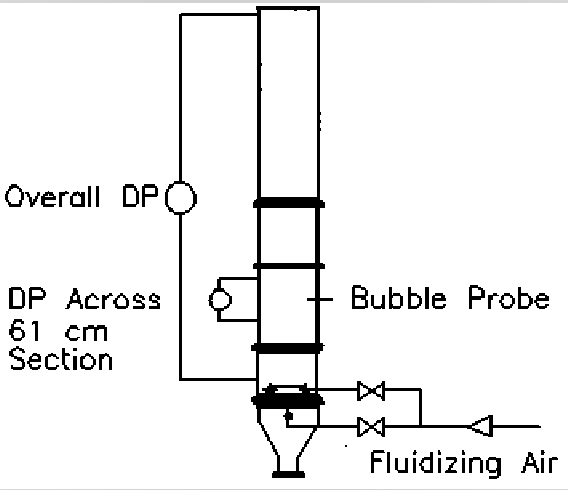
BFB geometry

Test Conditions

Case	Fines Content, % Less Than 44 micron	Static Bed Height	Superficial Gas Velocity at Bed Bottom	Air Distributor
	% < 44 micron	Hstatic, ft (m)	Ug, ft/s (m/s)	Type
1	3	12 (3.66)	1 (0.3)	Pipe Manifold
2	3	4 (1.22)	1 (0.3)	Pipe Manifold
3	3	8 (2.44)	2 (0.6)	Ring Sparger
4	12	8 (2.44)	2 (0.6)	Ring Sparger



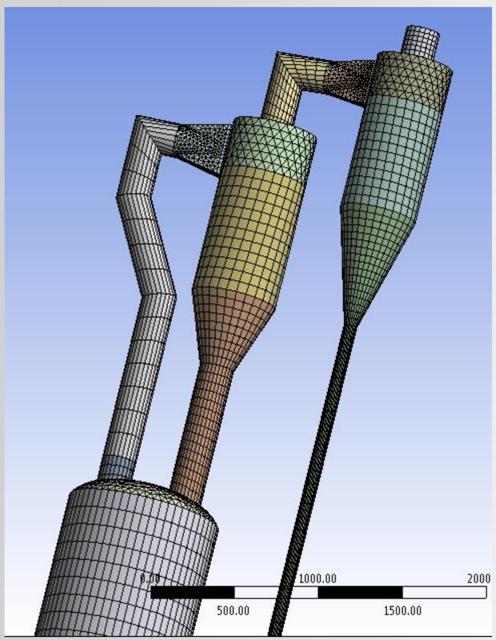
Experimental Measurements



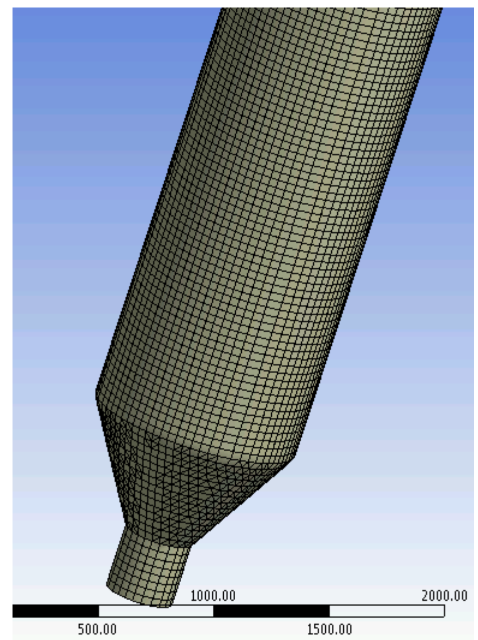
- Axial profiles of Pressure
- Differential Pressure (DP) fluctuations across entire bed and 24 inch section
  - Mean of DP corresponds to average solids mass
  - Std. Dev. of DP indicates fluidization quality
    - Smaller values – uniform fluidization
    - Larger values – poor fluidization or gas streaming
- Radial profile of bubble void fraction

Mesh

- Mesh generated on complete geometry as well as on truncated geometry (no cyclones)
  - Appropriate boundary conditions applied in truncated geometry simulations to maintain solids inventory



Complete Geometry



Truncated geometry
CutCell mesh

Results

- Eulerian-Eulerian and Eulerian-Lagrangian Model results are presented in following order
  - Eulerian-Eulerian Model (Euler-Granular with Population Balance)
    - Case 3
  - Eulerian-Lagrangian Model (DDPM)
    - Case 1 and Case 2 – effect of bed depth
    - Case 3 and Case 4 – effect of fines content

Case settings: Euler-Granular with population balance model

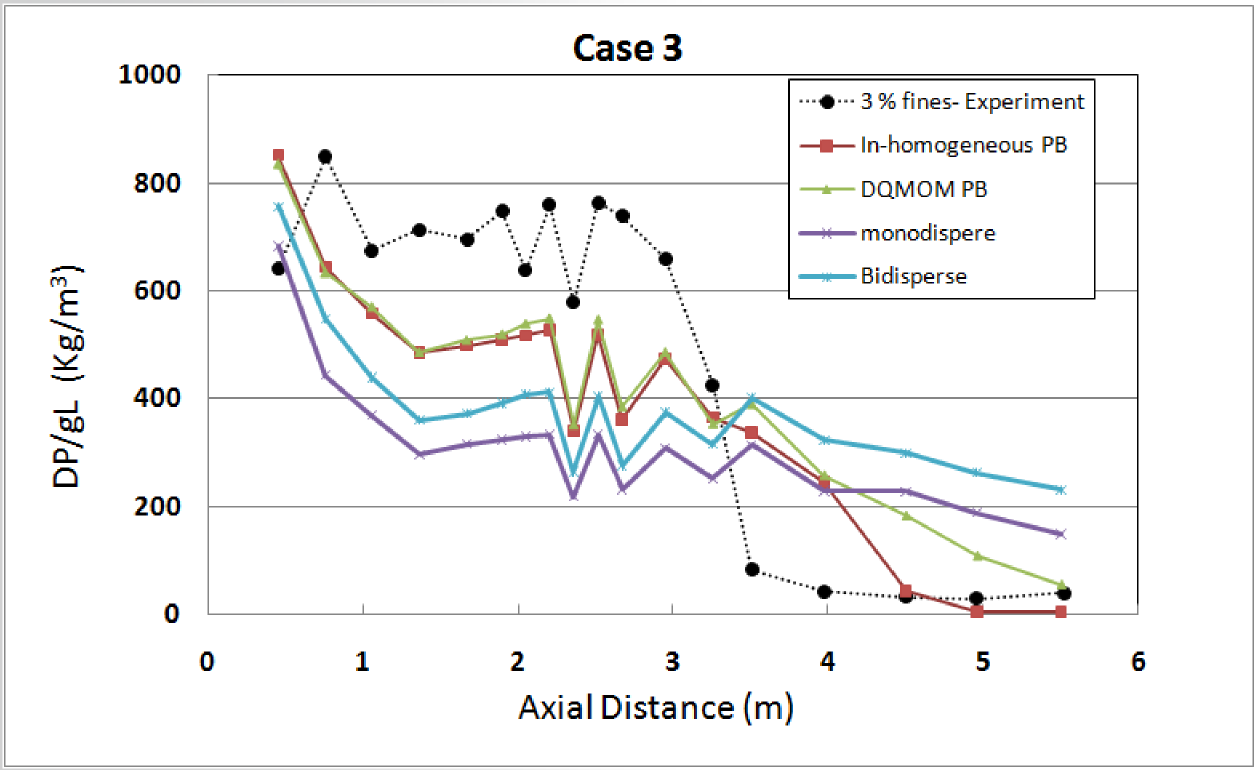
- Inhomogeneous discrete and DQMOM
  - Two granular phases plus 11 size classes (inhomogeneous) and three granular phases (DQMOM)
  - Granular kinetic theory based breakage and aggregation kernels (Fan et. al. 2004)
  - Modified Gibilaro and Foscale drag law
  - Rosin-Rammler representation of particle size distribution
  - First order discretization in time and space

- Computational cells 198000
- Time step 0.001 sec
- Time interval of averaging of results 80 sec
- Typical wall-clock time to simulate 1 sec of flow time 8 hrs on 20 processors

Results: Euler-Granular with population balance model

Case 3 : 3% fines, Static bed height 8 ft

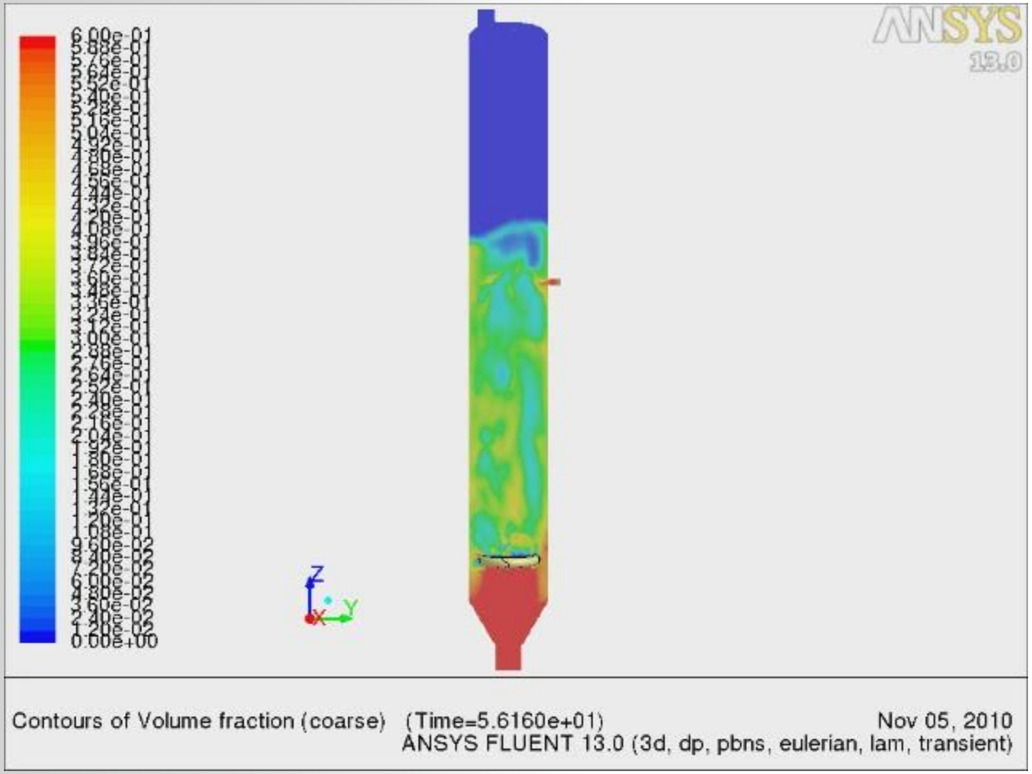
Axial Pressure Gradient Profile



Results: Euler-Granular with population balance model

Case 3 : 3% fines, Static bed height 8 ft

Inhomogeneous discrete

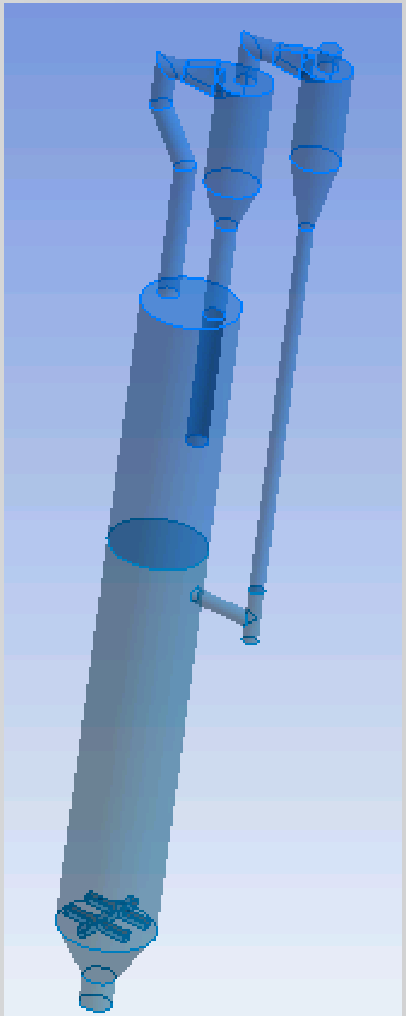


Case settings: Eulerian-Lagrangian (DDPM) model

- Granular kinetic theory based treatment of particle collisions
- Wen and Yu drag law
- Rosin-Rammler representation of particle size distribution

Computational cells	91000
Time step	0.001 sec
Number of parcels tracked	~ 1 million
Time interval of averaging of results	10 sec
Typical wall-clock time to simulate 1 sec of flow time	40 min on 20 processors

Results: Eulerian-Lagrangian (DDPM) model



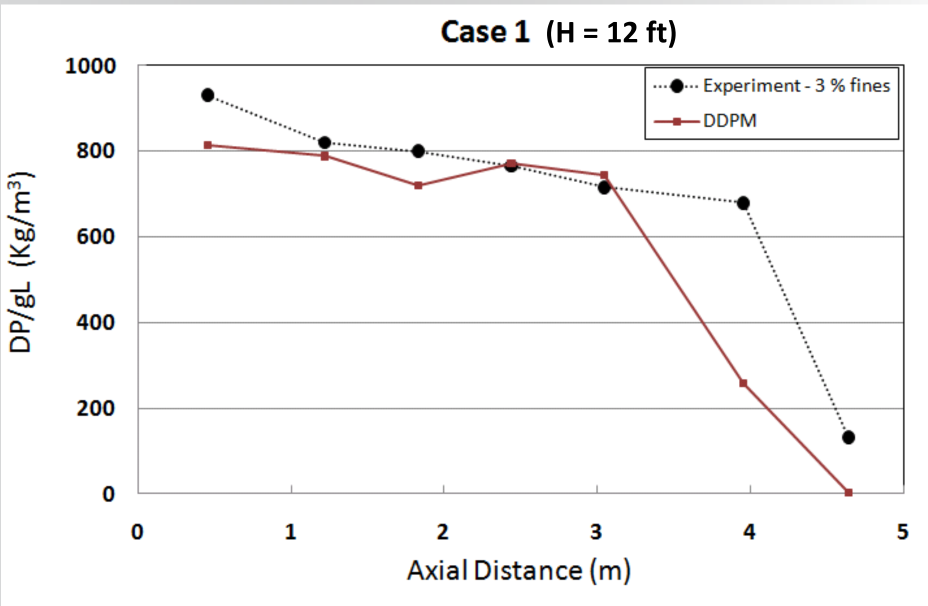
- **Effect of bed depth on fluidization behavior**

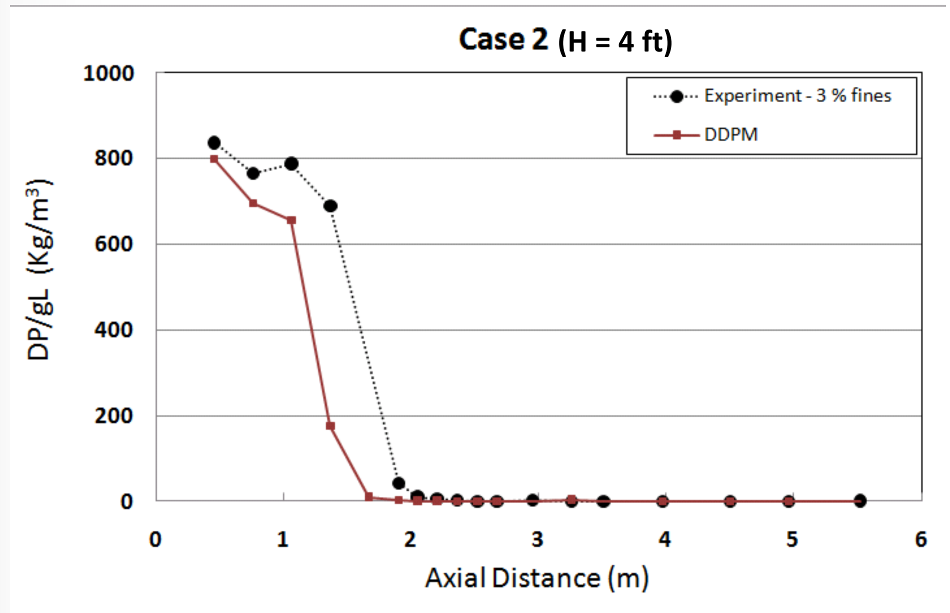
	Static Bed Height (H)
Case 1	12 ft
Case 2	4 ft

  - 3% fines content in both cases
  - Complete geometry considered for both cases
  - Air distributor type – pipe manifold

- Deeper bed has a tendency to exhibit gas streaming (larger fluctuations in DP) compared to shallow bed (Issangya et. al. 2007, Karimipour & Pugsley 2010)

Results: Axial Pressure Gradient Profile





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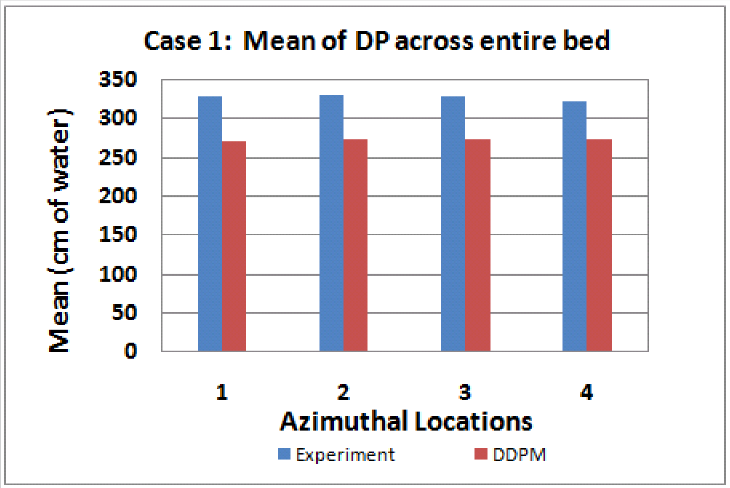
Results: Mean and Std. Dev. of Differential Pressure (DP) across entire bed and 24 inch section

Fig. 1



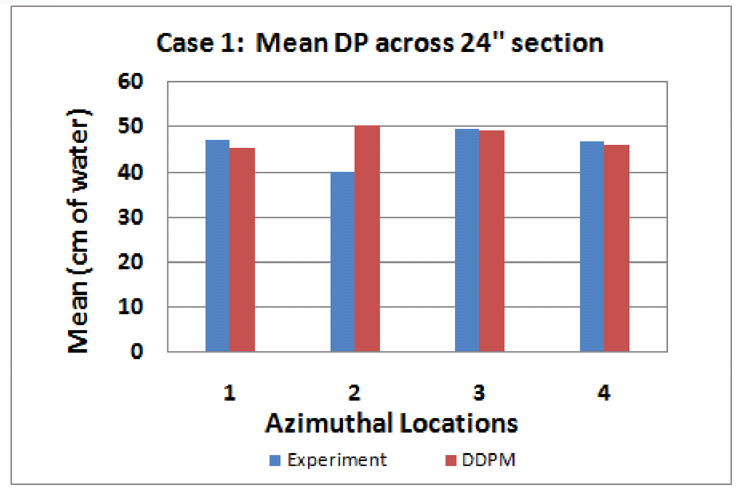
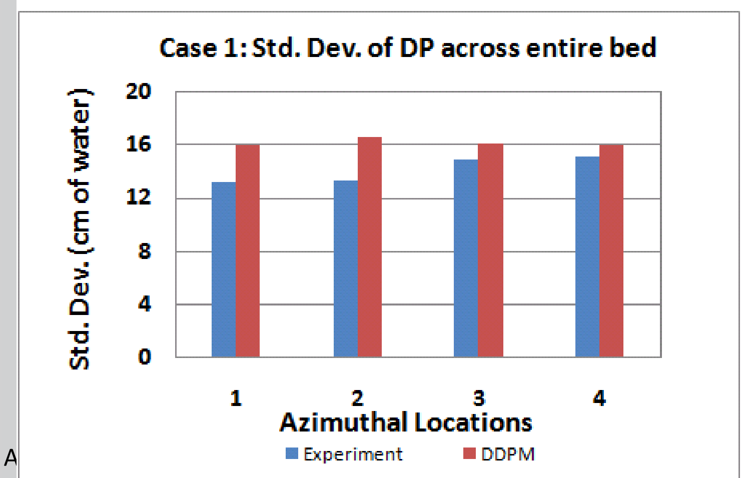


Fig. 3

Fig. 2



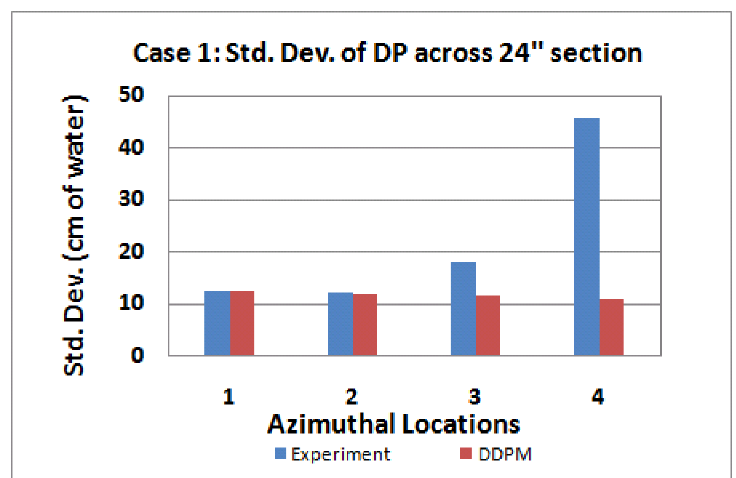
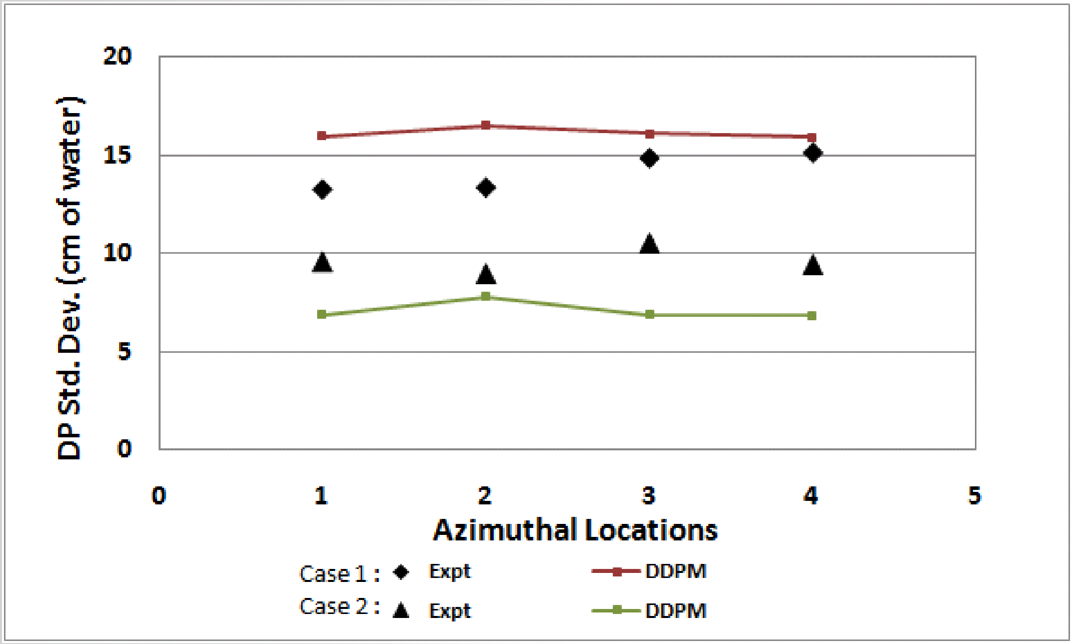


Fig. 4

Results: Effect of bed depth on fluidization behavior

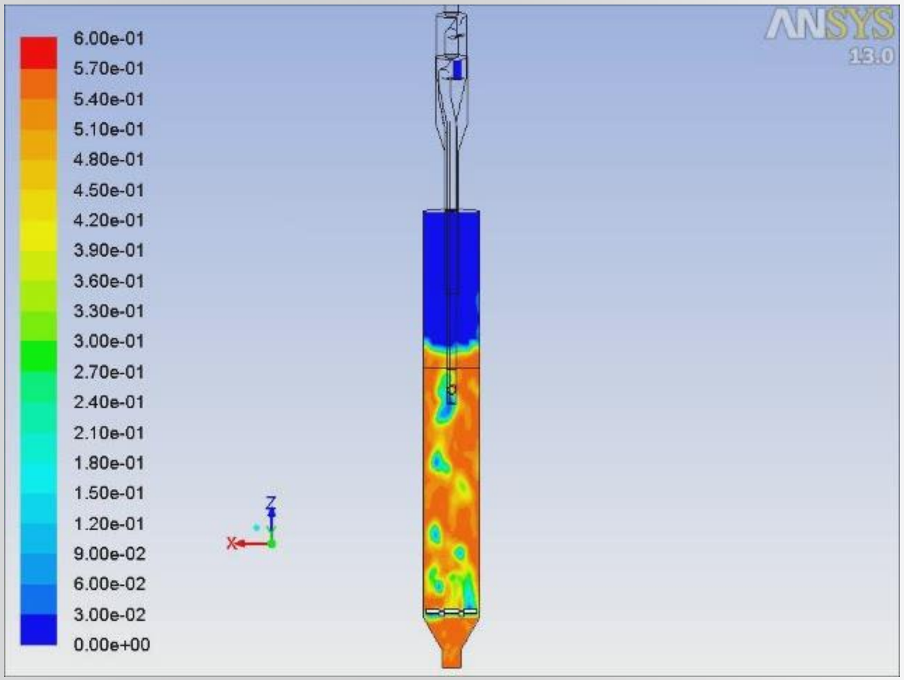
Std. Dev. of Differential Pressure (DP) across entire bed
Case 1: H = 12 ft and Case 2: H = 4 ft



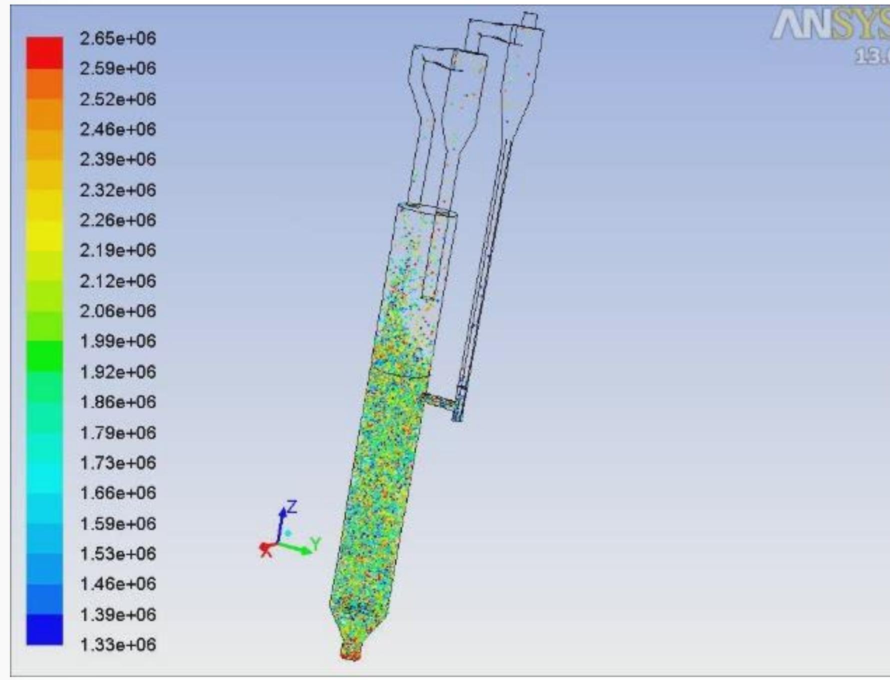
- Deeper bed has a tendency to exhibit gas streaming (larger fluctuations in DP) compared to shallow bed. DDPM model qualitatively predicts the trend as observed in experiments.

Results: Animations

Case 1

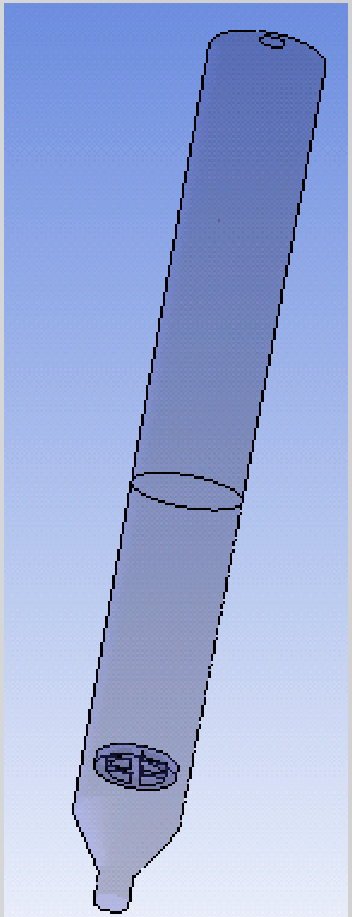


Contours of volume fraction of particles



Particle traces colored by particle ID

Results: Effect of fines content on fluidization behavior



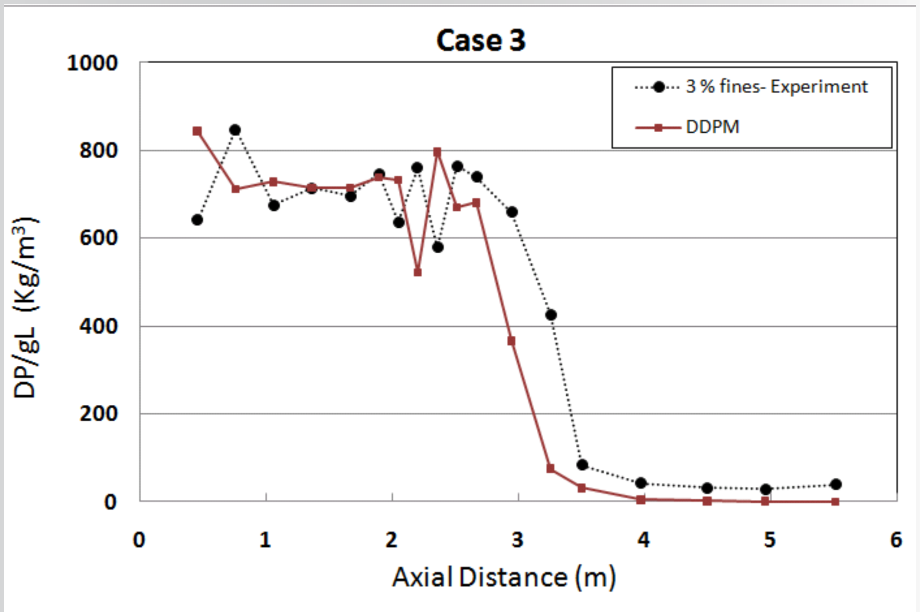
	Fines Content
Case 3	3 %
Case 4	12 %

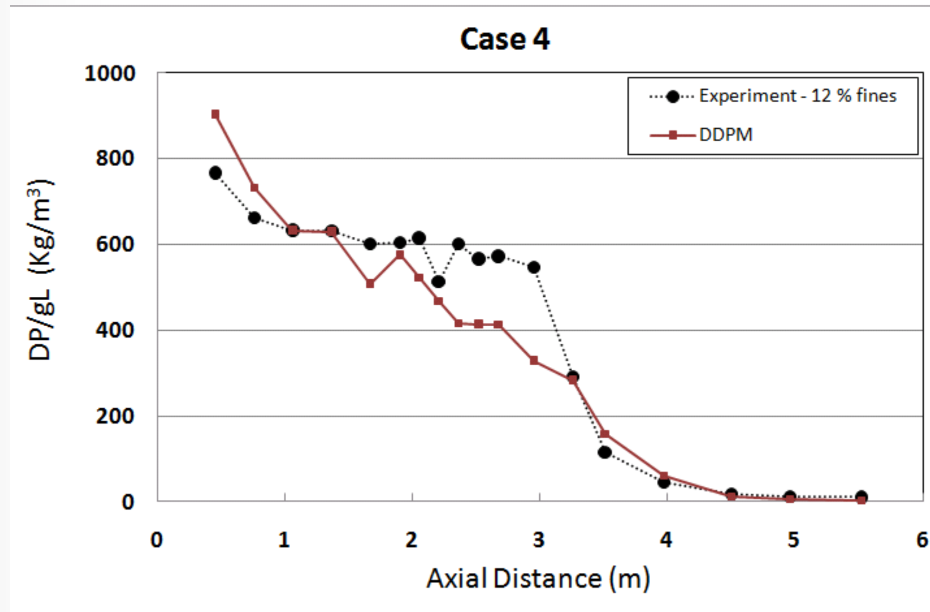
- 8 ft static bed height in both cases
- Air distributor type – ring sparger
- Truncated geometry considered for both cases
- Appropriate boundary conditions applied to maintain solids inventory

- Gas streaming intensity decreases (smaller fluctuations in DP) with an increase in fines content

(Issangya et. al. 2007, Karimipour & Pugsley 2010)

Results: Axial Pressure Gradient Profile





Results: Mean and Std. Dev. of Differential Pressure (DP) across entire bed and 24 inch section

Fig. 1

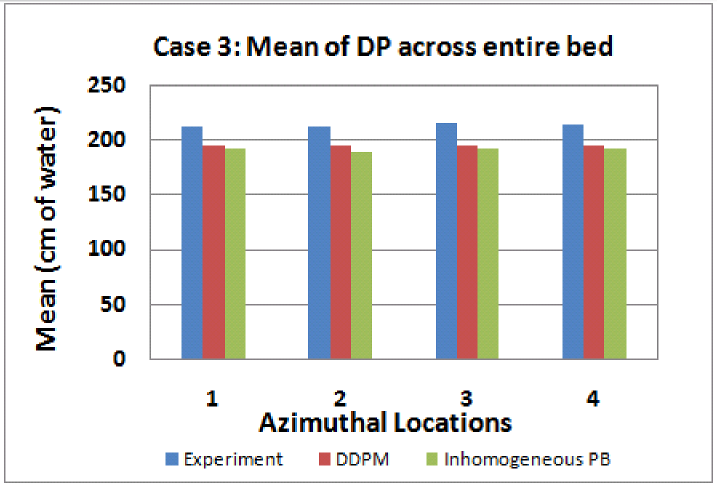


Fig. 3

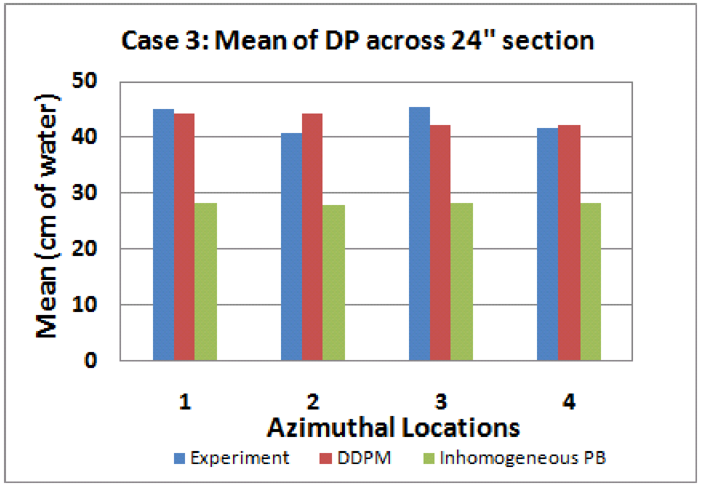


Fig. 2

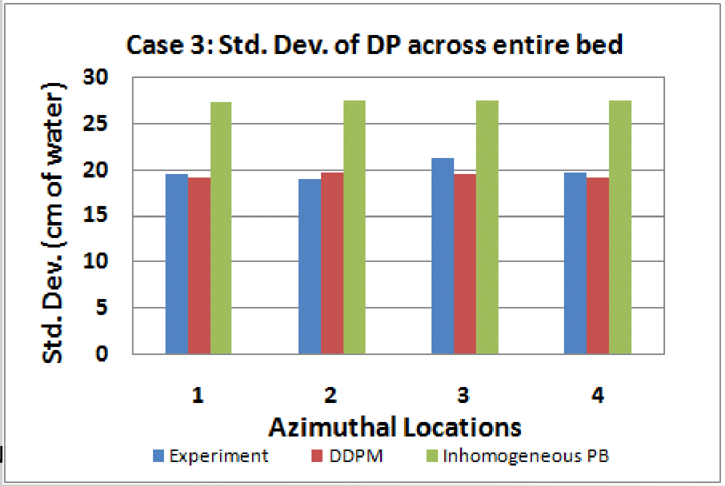
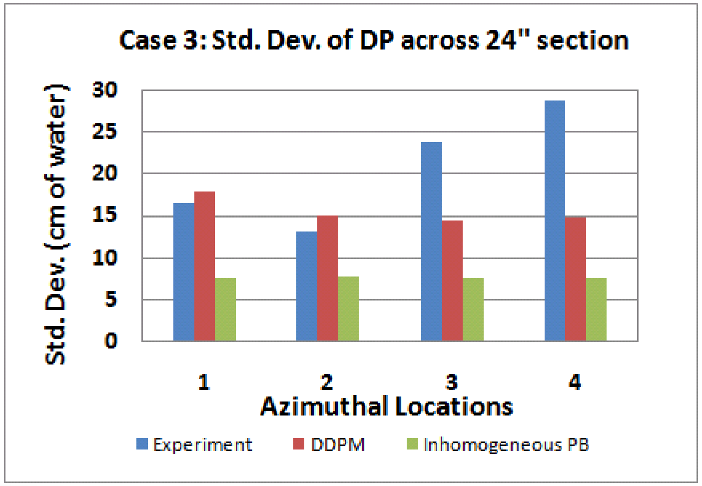
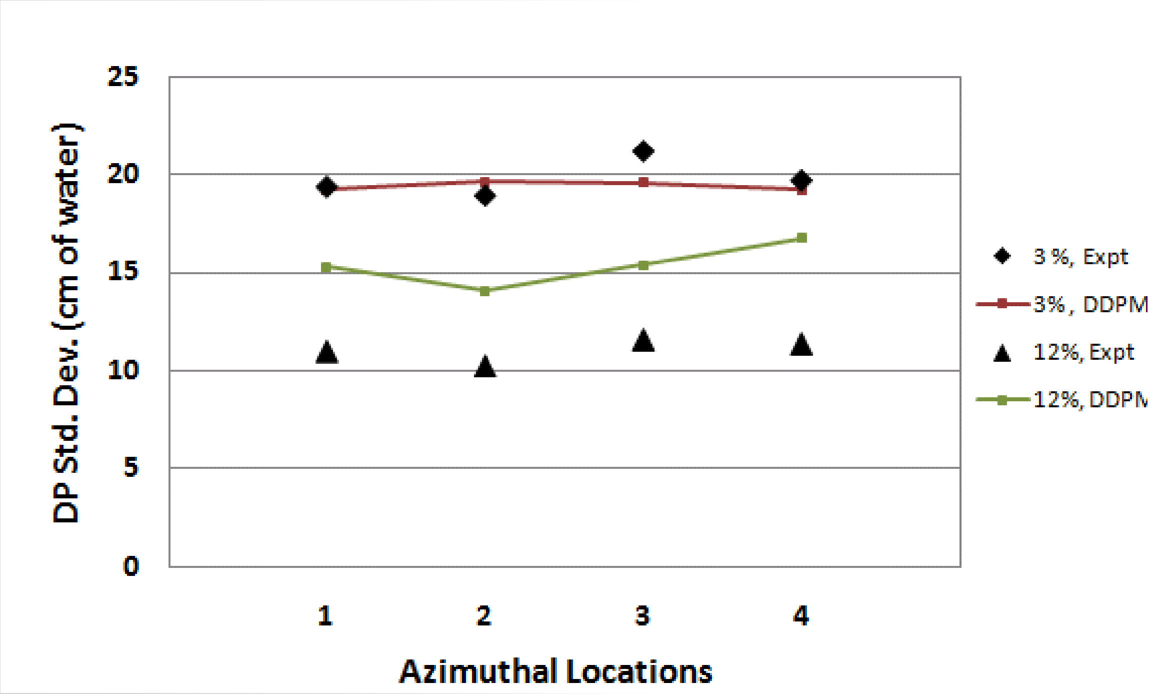


Fig. 4



Results: Effect of fines content on fluidization behavior

Std. Dev. of Differential Pressure (DP) across entire bed
Case 3: 3 % fines and Case 4: 12 % fines

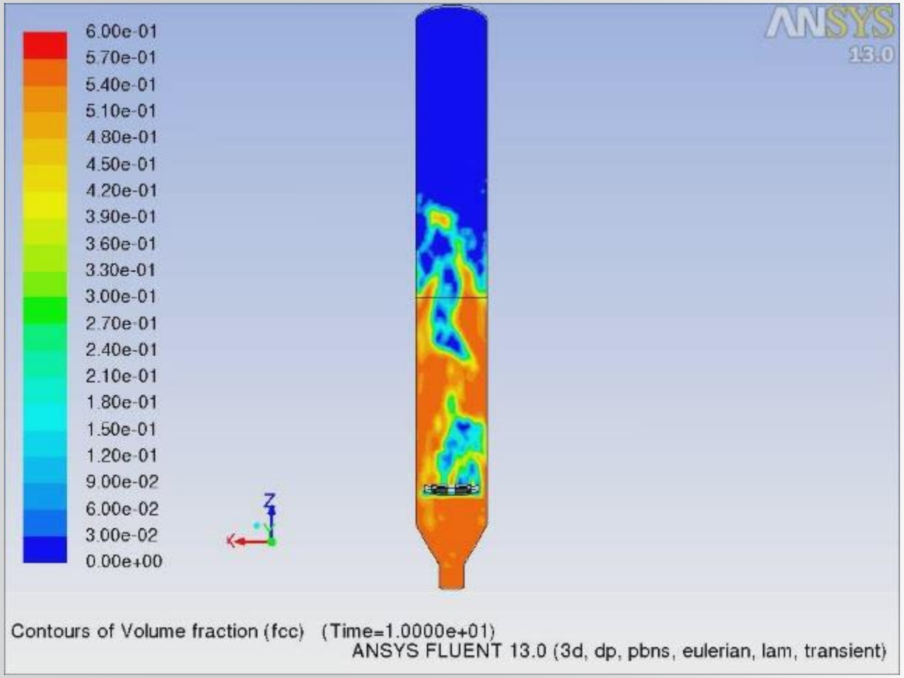


- Gas streaming intensity decreases (smaller fluctuations in DP) with an increase in fines content. DDPM model qualitatively predicts the trend as observed in experiments.

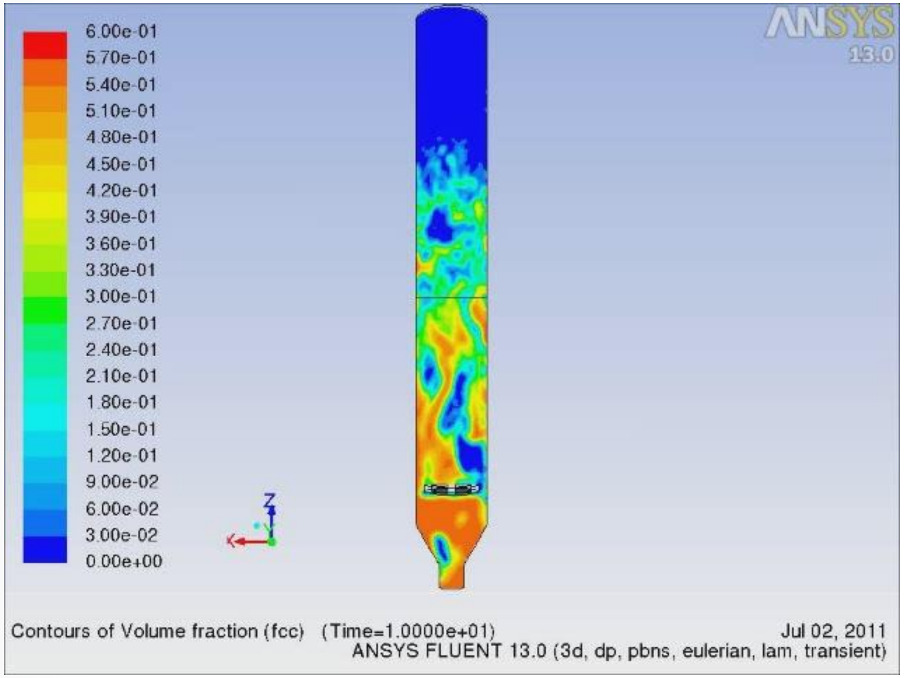
Results: Animations

Contours of volume fraction of particles

Case 3



Case 4



Summary

- Demonstrated the suitability of modeling platform for dense particulate flows
- Ongoing validation efforts to assess the performance and identify areas for improvement

Eulerian-Eulerian

- The E-E models clearly illustrate the benefits of including size distribution and phase separation through PBM

- In E-E models, typical drag laws do not capture the influence of meso-scales and so the choice of drag law is critical in predicting the correct bed height over long times

Eulerian-Lagrangian

- DDPM model qualitatively captures the differences in fluidization behavior with different bed depths and fines content

- DDPM model is applicable at all volume fractions and is also computationally efficient

